

Energy loss analysis of a large scale BIPV system for university buildings in tropical weather conditions: A partial and cumulative performance ratio approach

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HIGHLIGHTS

- Energy performance of BIPV fixed tilted roof system.
- Partial and cumulative performance ratios of BIPV system.
- Energy losses in BIPV system.
- Recommendations and suggestion for minimizing energy losses in BIPV.

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ABSTRACT

This paper evaluates and discusses the building-integrated photovoltaic (BIPV) system energy losses during the energy conversion process from sunlight into electricity. An approach based on partial performance ratio (P-PR) and cumulative performance ratio (C-PR) is used. The P-PR and C-PR are evaluated considering eight stages possible in the energy conversion stage in photovoltaic (PV) energy systems. A large-scale BIPV system is proposed by retrofitting the existing university buildings is investigated, and the observed results depict the impact of energy losses over the performance ratio decline. Results showed that the P-PR of the BIPV as per eight energy conversion stages varies between 85.6 and 100%. The C-PR varies between 74 and 100%, recording an overall system performance ratio (PR) of 74% under tropical weather conditions. The energy losses are varied within the range of -0.27 to -14.8% (-4 to -223 kWh/kWp) in different energy conversion stages. The total energy losses in the BIPV system account for 26% (-419 kWh/kWp). Based on the observations, reasons for various losses and their mitigation strategies are explored. Thus, we believe this study could provide useful information on the feasibility of considering retrofitting the university buildings with the BIPV modules.

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Nomenclature and abbreviations

AC	alternating current
$AC_{\text{cabling_loss}}$	losses in AC cables
BIPV	building-integrated photovoltaics
BIPV-R	building-integrated photovoltaic roof
BIPV-FTR	building-integrated photovoltaic-fixed tilted roof
C-PR	cumulative performance ratio
DC	direct current
$^{\circ}\text{E}$	east
EU	European Union
EP6	sixth framework programme
E_{sm}	monthly sum of specific electricity productions in kWh/kWp
E_{sd}	daily sum of specific electricity productions in kWh/kWp
E_{share}	percentual share of monthly electricity productions in %
G	global irradiation in kWh/Sq. m.
G_{shaded}	global irradiation reduced due to terrain shading in kWh/Sq. m
G_{angular}	global irradiation reduced by angular reflectivity in kWh/Sq. m
G_{monthly}	monthly sum of global irradiation in kWh/Sq. m
H	horizon
IEA	International Energy Agency
kWh	kilowatt-hour (one unit)
kWh/kWp	kilowatt-hour per kilowatt peak
kWh/Sq. m/kWp	kilowatt-hour per one square meter per kilowatt peak
kWh/Sq. m	kilowatt-hour per one square meter
MWp	megawatt peak
m	meter
MPP	maximum power point
MESoR	management and exploitation of solar resource knowledge
$^{\circ}\text{N}$	north
PV	photovoltaics
P-PR	partial performance ratio
PR	performance ratio
P_{DCoutput}	power losses during the energy conversion for the PV modules
P_{ACoutput}	power loss in the transformer and AC cabling
$P_{\text{ACinverter}}$	power losses during DC to AC conversion
SHC	solar heating and cooling
SE	Solar elevation
SA	solar azimuth
T	ambient temperature in $^{\circ}\text{C}$
TR_{losses}	transformer losses
TMY	typical meteorological year
V_{DC}	input DC voltage of the inverter
Sh_{losses}	losses of global irradiation by terrain shading
UMP	Universiti Malaysia Pahang
RtB	retrofitting the buildings
PHT	passive housing technology

1. Introduction

Urban infrastructure is one of the critical elements that has seen drastic and ever imaginable growth in modern society. Among the infrastructure, buildings are considered as the key elements that lodge diversified opportunities and occupations. Few studies suggest that the buildings consume 32% of the energy out of 100% global energy and contribute to greenhouse emissions [1–4]. The accounted greenhouse gasses related to this energy consumption are 19% [2,5]. Many ways are available to reduce this greenhouse gas contribution; these include energy efficiency, water efficiency, and material efficiency strategies in buildings [6]. A European Union (EU) report suggested that 90% of emissions released due to the buildings can be reduced using current sustainable technologies. On the other side, the European Commission is observing at best possible ways to tackle emissions from buildings in a cost-efficient way [7]. The three best possible practices are passive housing technology (PHT), retrofitting the buildings (RtB), and replacing fossil fuel electricity with renewables (FFER). Among the three practices mentioned above, PHT can be very well suitable for new buildings. RtB

can retrofit the old buildings, but the RtB is done by conducting reasonable feasibility simulations or survey-based studies in most cases. The FFER practice is most widely used either in old buildings or new buildings by replacing fossil fuel-based energy supplies with renewable and other sustainable energy technologies [8]. Though there exist three practices, the FFER methods are widely used in old and new buildings. Solar photovoltaics (PV) is one solution that preferably falls under FFER practices for building applications that could offset energy consumption and emissions. Keeping the concentration on building energy and environmental efficiency, building-integrated photovoltaics (BIPV) technology is identified to be the best offset in providing the building energy needs in viable conditions.

BIPV is one of the emerging technologies used for harnessing solar energy with solar PV/glass modules. Here the PV/glass modules are integrated into the building parts (example, roof, façade, canopy, etc.) rather than attaching to the building using extra support to mount solar panels like how we see in the rooftop plants [9]. The BIPV technology will act as a substitute material to conventional buildings covering materials with an additional advantage of electricity generation using solar PV [10]. The buildings can be converted into an energy generator where the produced energy can be utilized for self-energy consumption, and additional power can be sold to the utility. BIPV is one of the fastest-rising slices of the PV sector. Its significant pros in the extra marginal price that could take place during installation are more than balanced by the renewable electricity production [10,11]. Recent advancements in BIPV modules made this technology much more feasible on broader architectural design aspects [12]. For example, the flexible and lightweight glass/PV modules gave a path for easy integration to the building parts in an aesthetic and pleasing look. On the other side, the recent developments on PV module transparency gave the scope for semi-transparent/fully transparent BIPV technologies that allow having daylight saving possibilities apart from electricity generation [13–16]. All these favors the development and implementation of BIPV. However, the major drawback is the BIPV system's performance, as they are directly influenced by the environmental factors of the installation location, price, limitations in the market, and standards [17–20]. The performance varies concerning weather conditions as well as the BIPV system components chosen. Hence, the need to account for the energy losses in BIPV systems is much more essential to evaluate its feasibility. Various studies were conducted on BIPV systems concentrating on performance, materials and products, performance monitoring, installation designs, etc., in literature [21–32]. In Ref. [13], the BIPV glazing system's lifetime performance is investigated, and the results revealed that the system has favorable energy outputs in tropical environments. In another study, Kumar et al. investigated the BIPV performance by comparing the two different installation approaches (vertical BIPV and horizontal BIPV). It was suggested that horizontal BIPV has more significant energy outputs, and they made it clear that, as the tilt angle increases, the energy outputs for BIPV would reduce [14]. Akata et al., in Ref. [19], analyzed the energy performance of the BIPV roof planned for a residential apartment in Cameroon in the tropical environments, and it was suggested that the proposed system could meet daily energy demands. In Ref. [21], Li et al. conducted a real-time investigation based on the monitored data. Yadav et al. [22] determined the BIPV system optimum tilt and azimuth angle by accounting for the neighbouring buildings' shadow conditions. A model based on shading coefficient and sky-view factor was proposed to evaluate solar irradiation incident on the BIPV array accurately in another study, and accordingly, the energy performance was analyzed [23]. In addition to the above discussed two investigations by Yadav et al., in Refs. [22,23], few more studies suggest that we consider the optimal tilt and azimuth angle while investigating the BIPV [24–27]. Kumar et al. [28] showed that different PV cell technology has a considerable influence on the energy outputs. Besides, it is also suggested that the energy performance of BIPV is varied based on roof and façade directions [29], and they are verified by conducting simulation studies; details can be seen in Ref. [30] for single sloped pitched roof [31], for a double sloped pitched roof. Gholami et al. investigated the BIPV performance considering Solsmaragden building in Norway as a case study and concluded that energy performance is varied concerning orientation and panel arrangement [32].

However, most of the studies were conducted for already developed nations and various weather conditions. As we know, BIPV

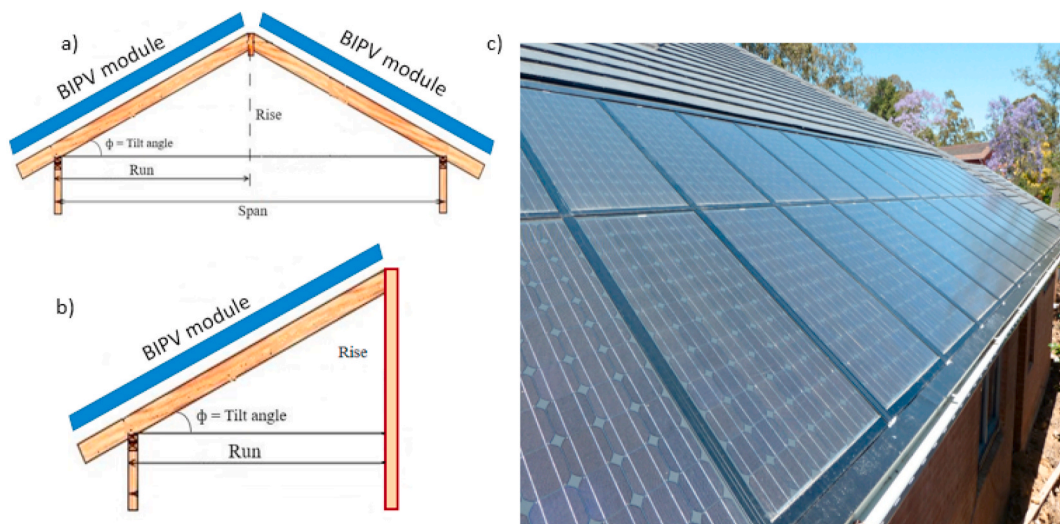


Fig. 1. a) Double slope roof, b) Single slope roof, c) BIPV roof building.

systems exhibit their performance concerning the installation site due to the influence of local weather parameters. Thus, it becomes a fundamental challenge to understand its feasibility under tropical weather conditions. The research studies in the literature suggest having focused observations on the energy performance of the BIPV systems as the energy measures the quantity [21–32]. However, another critical parameter to be observed is the loss, which is an essential element to improve the performance. Hence, in this paper, we study the various possible losses in the BIPV system, starting from the incident solar irradiance on to the BIPV module to the final electricity generations. This study considered whether parameters in tropical weather conditions and system parameters during the energy loss evaluation. The investigation on energy losses is carried out by performing a simulation study by dividing the energy conversion process in the BIPV system into eight stages. In each energy conversion stage, various energy indicators, such as specific energy yields, electrical potentials, energy losses, were evaluated. Finally, the corresponding partial performance ratios (P-PR) and the cumulative performance ratios (C-PR) were assessed.

2. Building integrated photovoltaic-fixed tilted roof

The BIPV system integrated on a building roof at a certain angle is called Building Integrated Photovoltaics-Fixed Tilted Roof (BIPV-FTR). A typical BIPV-FTR with the double sloped and single sloped roof is shown in Fig. 1.

From Fig. 1, it can be understood that the BIPV modules are architecturally integrated considering the building architecture and design aspects. Here, the design issues related to orientation and tilt position of the roof or façade have to be considered (this is only applicable with respect to the building infrastructure). However, most of the counties' residential buildings were roof-based, categorized into double slope roofs and single slope roofs (Fig. 1). The possible tilt angle is estimated based on the building roof rise and run or span (see in Equation (1)) [33].

$$\theta = \tan^{-1} \frac{\text{Rise}}{\text{Run}} \quad (1)$$

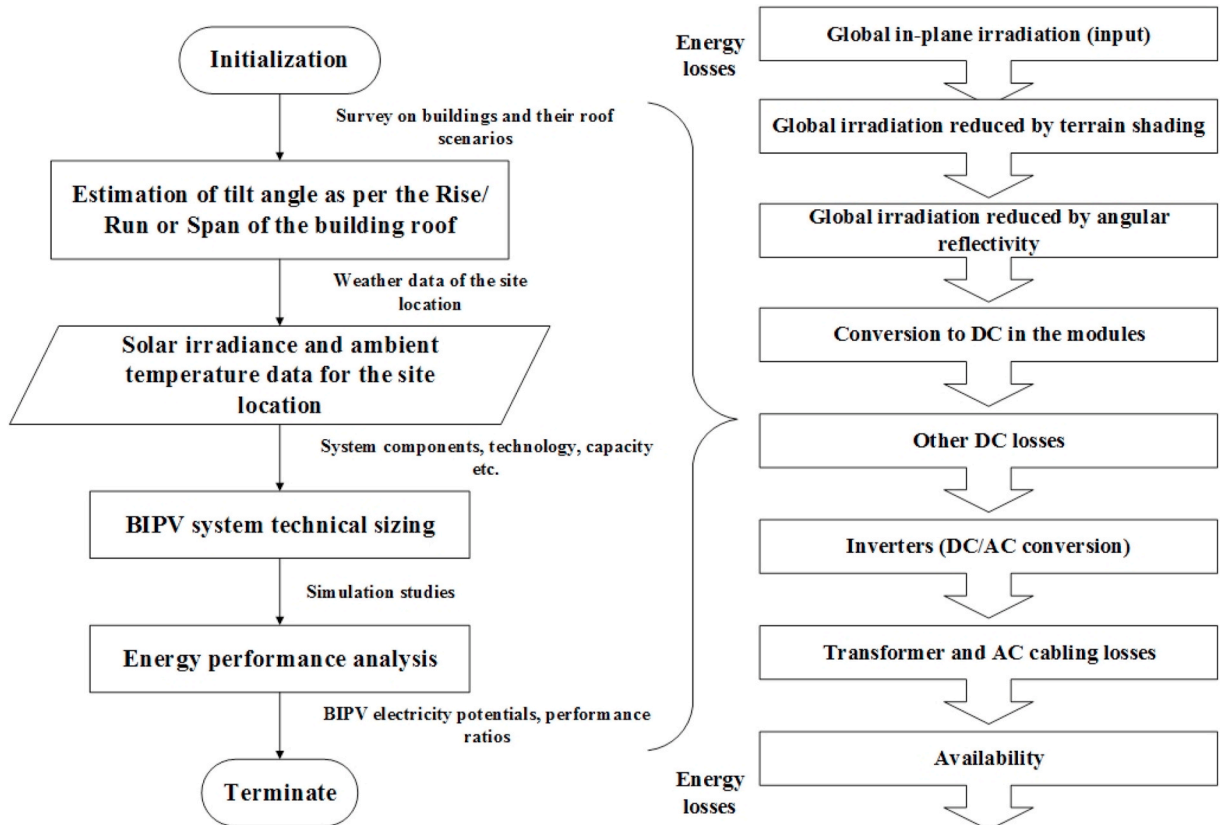


Fig. 2. Methodology adopted for loss evaluation in BIPV system.

3. Methodology

3.1. Study location

The BIPV-Roof system was proposed for a Universiti Malaysia Pahang (UMP), Pekan campus in Malaysia. The UMP Pekan campus is geographically located in the Pahang State of Peninsular Malaysia at a Latitude – 3.544 N, Longitude – 103.429 E, and the elevation from the sea level is 12 m. The UMP experiences tropical weather conditions, mostly maintaining similar weather parameters throughout the year. The Universiti has well-established policies and frameworks that help achieve sustainable and green metrics ranking by UI Green Metric World University Ranking [34]. As a part of this, sustainable initiatives like renewable energy usage, energy efficiency, water efficiency, and resource efficiency were prioritized [35]. To promote UMP building's sustainability, a BIPV system is proposed to help in terms of electricity generations and land conservation. The proposed BIPV system is as per the existing building configurations. A critical study on the UMP infrastructure reveals that most buildings were categorized into single slope roofs and double slope roofs. Hence, the possible PV configuration is BIPV-Roof. However, the building roof is at a slope creating an angle, making provision to install the BIPV module at a fixed tilt angle.

3.2. Performance modelling of BIPV

The proposed methodology used for investigating the energy losses in BIPV is represented schematically in Fig. 2. It is a five-step sequential flow methodology involving the complete performance study of the BIPV system.

The estimated energy losses were investigated based on the quality performance indicator (i.e., performance ratio). In the above-mentioned five-step sequential flow methodology, at each stage of the energy conversion process, we estimated the performance ratio in two ways, i.e., partial performance ratio and cumulative performance ratio.

3.2.1. Partial performance ratio

The partial performance ratio measures the expected energy output at each stage of the energy conversion step for the given monitoring period accounting for the relevant parameters that influence the BIPV system performance. The partial performance ratio of each energy conversion step would be higher than the cumulative performance ratio.

3.2.2. Cumulative performance ratio

The cumulative performance ratio measures the expected energy output by considering partial performance ratios of the previous energy conversion step for the given monitoring period accounting for the relevant parameters that influence the BIPV system performance. In cumulative performance ratios, we can directly add the energy losses (as the sign of the loss parameter is negative, the resultant would be negative), and accordingly, the ratio is estimated.

3.3. Energy loss assessment factors in BIPV system

Energy loss assessment in a BIPV system is evaluated using the following modeling equations. The evaluation is carried out as per the IEA SHC Task 36 (Solar Heating and Cooling Programme, International Energy Agency) and EU FP6 project MESoR standards [36–39].

3.3.1. Global irradiation reduced by terrain shading

The global irradiation that is going to an incident on the BIPV array is reduced or slightly varied, and this is due to the terrain shading. For the BIPV systems installed in the free areas, the terrain shading is mostly estimated using Equation (2) [40]. The global irradiation reduced by terrain shading will be the function of global irradiation (G), horizon (H), solar elevation (SE), and solar azimuth (SA).

$$G_{Shaded} = f_{shaded}(G, SE, SA, H) \quad (2)$$

3.3.2. Global irradiation reduced by the angular reflectivity

Global irradiation that is reduced by terrain shading is further reduced with angular reflectivity. This is due to the sun's relative position and the BIPV module plane onto which the solar radiation is falling. Global irradiation reduced by angular reflectivity is estimated using Equation (3) [40]. It is a function of terrain shaded irradiation (G_{Shaded}), clearness, the texture of BIPV module and properties, solar elevation (SE), solar azimuth (SA).

$$G_{Angular} = f_{Angular}(G_{Shaded}, SE, SA) \quad (3)$$

3.3.3. Conversion to DC in the modules

Losses in the PV modules during the conversion of light energy into DC energy are estimated using Equation (4) [40]. The DC energy produced in the BIPV module is the function of the global irradiance after the angular reflection losses ($G_{Angular}$), ambient temperature (T) of the BIPV module, and BIPV module type. The performance model expressed here represents the nonlinear behavior of the BIPV module during the energy conversion. Apart from the module parameters, losses possible due to mounting configuration

also. This stage is where maximum losses are accounted for during the energy conversion process and typically relatively high for crystalline silicon-based BIPV modules than thin-film BIPV modules.

$$P_{DC_Output} = f_{DC_Output}(G_{Angular}, T, BIPV \text{ Module Type}) \quad (4)$$

3.3.4. Other DC losses

Other DC loss accounts in the BIPV system are expressed by Equation. 5, i.e., shown as follows [40]. The defined Equation (5) considers the other DC losses due to inter-row shading, losses due to power tolerance, mismatch losses, and DC cabling losses.

$$P_{DC_Output_Effective} = f_{DC_Losses}(P_{DC_Output}, \text{Sum of the DC losses}) \quad (5)$$

BIPV inter-row shading losses: Inter-row shadings are possible during the BIPV array configuration topologies used. The arrangement of BIPV modules during the installation may have a short distance or nearby module shade. This results in energy loss contributing to one of the performance parameters. The inter-row shading influence on the electrical potentials will vary for each BIPV technology. Among the existed BIPV/PV technologies, crystalline technology is more sensitive.

Losses due to power tolerance of modules: The power tolerance of the BIPV or PV modules will result in uncertainties or fluctuations in the output electricity potentials. This loss occurs during the arranging of the BIPV array configuration. Based on the BIPV module power tolerance value, they are connected either in series or parallel. If the BIPV modules with higher power tolerance values are interconnected in series, then the possible losses are more elevated and vice versa.

Losses due to mismatch and DC cabling: Mismatch losses are possible in the BIPV system due to variation in the MPP operating point of the BIPV array connected to a DC-AC power converter. DC cabling losses are possible in the form of heat losses in the components' interconnections using cables.

3.3.5. Inverters (DC-AC conversion)

Inverters are used in the BIPV system to convert the DC output of the BIPV array into AC energy. It is one of the high efficient components of the BIPV system. Even though they are efficient, there are still chances of energy loss; this is due to the dependence on the load on the inverter and inverter DC input voltage. The losses due to the inverter can be estimated using Equation (6) [40]. It is a function of adequate DC output power ($P_{DC_Output_Effective}$) and DC system voltage (V_{DC}), where the output of the BIPV array is connected with inverter input.

$$P_{AC_Inverter} = f_{Inverter}(P_{DC_Output_Effective}, V_{DC}) \quad (6)$$

3.3.6. Transformer and AC cabling losses

DC energy converted into AC energy using the inverter is available as the output and is fed to the utility grid through the transformer. During this stage, some loss is possible, and they are quantified as Transformer and AC cabling losses using Equation (7) [40]. It is a function of inverter output ($P_{AC_Inverter}$), AC cabling losses ($AC_{Cabling_Loss}$), and transformer loss (TR_{Loss}).

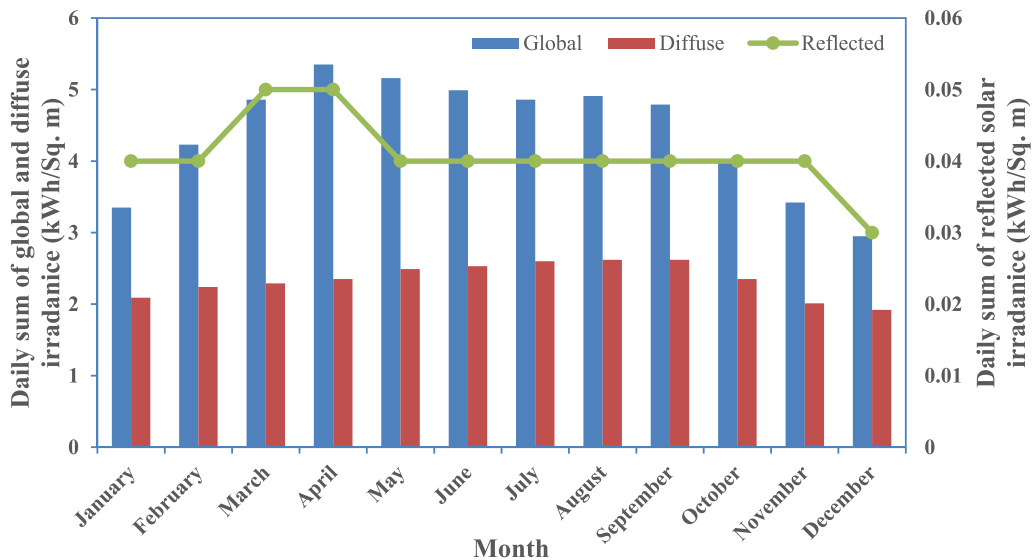


Fig. 3. The daily sum of global, diffuse, and reflected irradiance.

$$P_{AC_Output} = f_{AC_Output} (P_{AC_Inverter}, AC_{Cabling_Loss}, TR_{Loss}) \quad (7)$$

3.3.7. System availability

Availability is one of the parameters that have to be considered during the performance evaluation of the BIPV system. This parameter allows the PV system operator to quantify the energy losses possible due to the BIPV system's shutdown. In many cases, the system's shutdown is likely due to its failure and maintenance or a specific component. In this study, this loss is considered to be -1% , but it can be estimated as a function of three different parameters as represented in Equation (8) [41].

$$P_{Output} = f_{Grid_Availability} (P_{AC_Output}, Availability, Grid\ Regulation) \quad (8)$$

4. Results and discussion

We considered Malaysia's tropical weather conditions and a typical 1 MWp crystalline technology-based BIPV system proposed for retrofitting the UMP campus buildings to carry out the energy loss analysis. This study's results are shown in the below solar potential assessment, BIPV-roof electricity potentials, cumulative and partial performance ratio as per the energy conversion stages, and the energy losses.

4.1. Weather potential assessment

Solar potential assessment results are presented and discussed in this section. The daily sum of global, diffuse, and reflected irradiance in kWh/Sq. m for the study location throughout the year are shown in Fig. 3. The solar irradiance tends to increase and decrease throughout the year, having the highest peak value in April and the lowest in December. The daily sum of global irradiance under tropical weather conditions rises from a value of 3.35 kWh/Sq. m in to a peak value of 5.35 kWh/Sq. m from January to April, the variation is not much between April (5.35 kWh/Sq. m) to September (4.79 kWh/Sq. m). A drastic decrease in global irradiance is seen from September to December, i.e., from 4.79 to 2.95 kWh/Sq. m. However, the highest value of the daily sum of global irradiance is seen in April month, and the lowest value is seen in December month. Similarly, the daily sum of diffuse irradiance under the same tropical weather conditions maintained a close relationship. The variation is observed to be in the range of 1.92 kWh/Sq. m in December to 2.62 kWh/Sq. m in August and September. The daily sum of reflected irradiance at the site location is observed to be constant (i.e., 0.04 kWh/Sq. m) almost every month. However, a slight deviation, i.e., 0.05 kWh/Sq. m, is observed in March and April, and 0.03 kWh/Sq. m in December.

Monthly solar irradiance, shading terrain loss and air temperature at site location are presented in Table 1. The monthly solar irradiance on the BIPV module at optimal tilt angle tends to vary from 92.4 kWh/sq. m/kWp (recorded as the lowest value, i.e., in the December month) to 160.5 kWh/sq. m/kWp (recorded as the highest value, i.e., in the April month).

The yearly solar irradiance falling on the BIPV module is observed to be 1613 kWh/sq. m/kWp. Shading terrain losses in solar irradiance are observed, and they vary between 0.2 and 0.4%, recording overall value for a year at 0.3%. The ambient temperatures at the site location increase from January to May then decrease till the end of the year, i.e., December. Variation in ambient temperature is seen from 25.1 °C (i.e., for January) to 27.3 °C (i.e., for May), recording an average yearly value of 26.4 °C.

4.2. BIPV roof electricity potentials

The electrical energy generations and energy losses are estimated throughout 8760 h based on the weather input data given to the SolarGIS model in the form of a typical metrological year (TMY) file. The inclination angle is considered as per the building roof architecture, i.e., roof pitch. Mostly the buildings in the site location are constructed with an inclination of 30° are higher. Results revealed that a BIPV system could perform with a 74% performance ratio on average under Malaysia's tropical weather conditions, and the remaining 26% is left as losses in the BIPV system. The monthly sum of total electricity production, along with the average value, is

Table 1
Solar radiation, shading terrain loss, and air temperature at the site location.

Month	G _{monthly}	Sh _{losses}	Temperature (T)
January	104.8	0.4	25.1
February	118.6	0.3	25.9
March	150.5	0.2	26.4
April	160.5	0.2	27.0
May	160.1	0.2	27.3
June	149.7	0.2	27.1
July	150.7	0.3	27.0
August	152.3	0.3	26.9
September	144.7	0.3	26.9
October	125.4	0.3	26.4
November	103.7	0.3	25.7
December	92.4	0.4	25.2
Year	1613.4	0.3	26.4

shown in Fig. 4. The average monthly amount of electricity produced in the BIPV system was 99441.66 kWh, accounting for the cumulative amount of electricity produced for 12 months was 1193300 kWh. While the produced electricity from the BIPV system was varied for months, this is due to the variation in the input global in-plane irradiance and its effects on the system performance parameters. In the proposed system, 118400 kWh was recorded as the highest electricity potential in April, while the lowest electricity produced was 68300 kWh in December. However, a considerable variation in the electricity potentials was observed in most of the months, and the range of variation was almost 1.73 times between the highest and recorded months.

Table 2 summarizes the BIPV system electricity potentials in the form of a monthly sum of specific electricity productions in kWh/kWp, the daily sum of specific electricity productions in kWh/kWp percentual share of monthly electricity produced in %. The highest monthly and the daily sum of specific electricity productions were recorded as 118.4 kWh/kWp and 3.95 kWh/kWp, respectively, in April. While December was recorded as the month where monthly and daily specific electricity productions are lowest with 68.3 kWh/kWp, and 2.20 kWh/kWp, respectively. On the other hand, every month's percentual share of electricity production was observed to vary in the range of 5.7–9.9%. The reason for the variation in the percentual share of electricity production was due to the variation in solar irradiance incident on the BIPV modules or the BIPV system. Most of the months (March, April, May, June, July, August, September) have contributed the maximum share of electricity productions having a slight variation, i.e., from 8.9 to 9.9%. While in the rest of the months (January, February, October, November, December), the percentual share was between 5.7 and 7.8%.

4.3. Cumulative and partial performance ratios

The typical BIPV system's electricity production could significantly get influenced by various system parameters that reduce energy during photovoltaic energy conversion. Hence the electrical performance of the BIPV system could be evaluated considering the performance ratio. Therefore, the performance ratio of 1 MWp BIPV system every month for tropical weather conditions was assessed, and the same was charted in Fig. 5. A 1 MWp BIPV system's performance ratio over an average year is estimated to be 74%. However, the monthly variation range of performance ratio was observed as 73.6–74.8%.

Fig. 5 shows the performance ratio of the BIPV system concerning the energy conversion stages, where the energy losses were accounted. In each stage of the energy conversion process, partial amounts of energy were lost. This gives the scope for evaluating the partial performance ratios during the energy conversion at individual stages.

The performance ratio was assumed to be 100% in the condition where, entire incident global in-plane irradiation is converted into electricity, but it is not possible. The partial performance ratios in the global irradiation reduced by terrain shading, global irradiation reduced by angular reflectivity conditions were observed as 99.7% and 96.4%, respectively. Similarly, the partial performance ratios at module-level DC energy conversion and other DC losses were 85.6% and 94.5%. P-PR at power conversion (DC to AC using inverters) and transmission stage (Transformer and AC cabling) were noted to be 97.5% and 98.5%, respectively. Considering the BIPV system availability conditions, the PPR would be 99%. However, an average yearly performance ratio of 74% indicates a well functioning of the BIPV system for tropical weather conditions. This average annual performance ratio was quantified by adding the possible losses during the energy conversion process from sunlight incident on the BIPV module to electricity. Careful observation from Fig. 6 shows that the cumulative performance ratios at each stage influence the previous energy conversion stage resulting in the final system performance ratio at the endpoint.

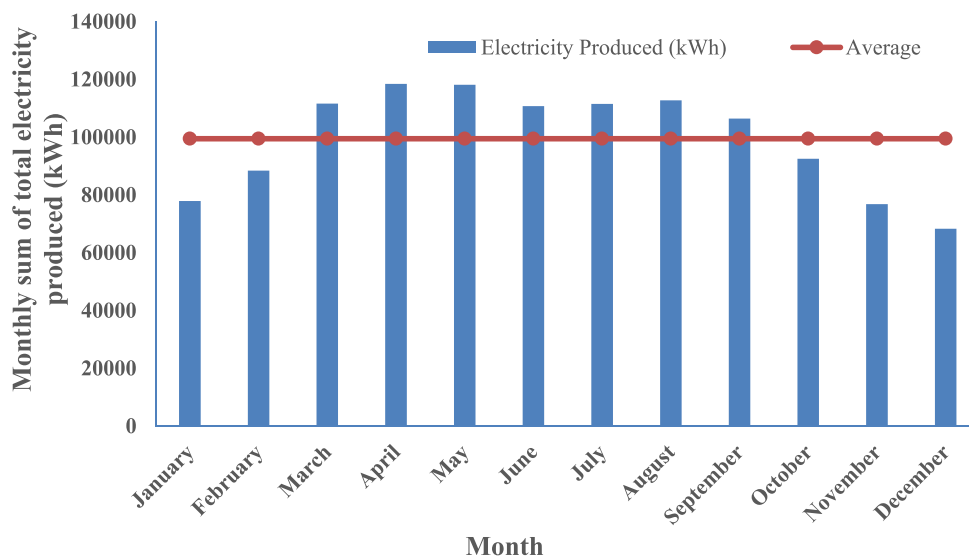


Fig. 4. Monthly sum of total electricity production.

Table 2
BIPV roof electricity potential.

Month	E_{sm} (kWh/kWp)	E_{sd} (kWh/kWp)	E_{share} (%)
January	77.9	2.51	6.5
February	88.4	3.16	7.4
March	111.6	3.60	9.4
April	118.4	3.95	9.9
May	118.1	3.81	9.9
June	110.7	3.69	9.3
July	111.5	3.60	9.3
August	112.7	3.64	9.4
September	106.4	3.55	8.9
October	92.5	2.98	7.8
November	76.8	2.56	6.4
December	68.3	2.20	5.7
Year	1193.3	3.27	100.0

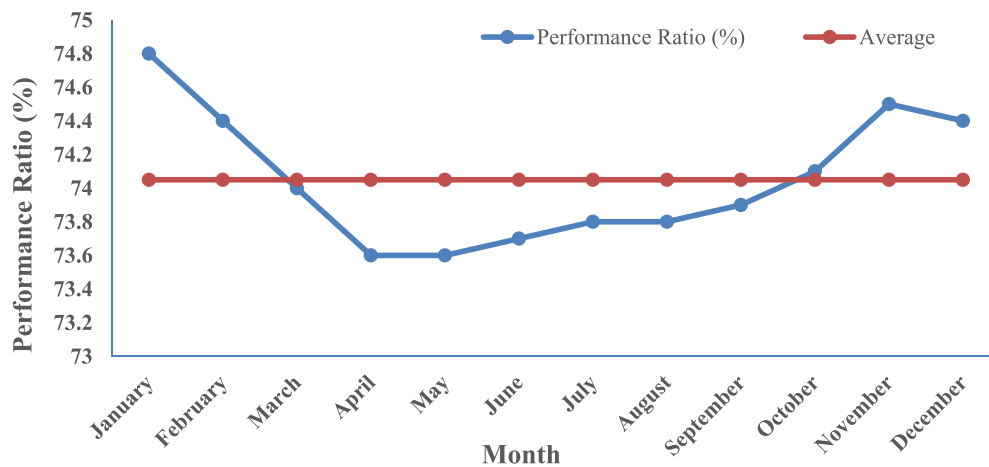


Fig. 5. Monthly performance ratios of BIPV system.

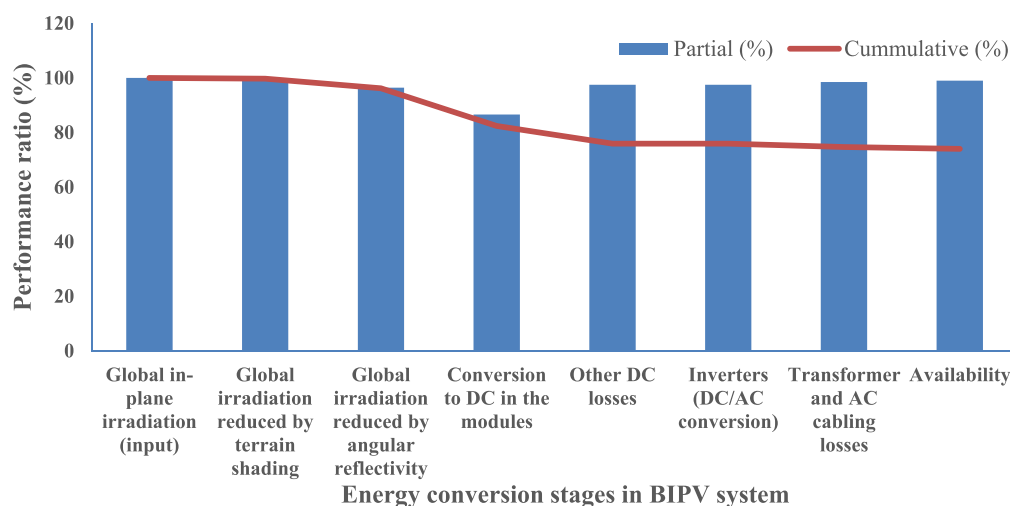


Fig. 6. Performance ratio of BIPV system concerning the energy conversion stage.

4.4. Energy losses in BIPV system

The energy loss diagram of the 1 MWp BIPV system was shown in Fig. 7. Various losses in the system were quantified and presented in percentages. For a clear understanding, the BIPV system performance is subdivided into three; input stage, energy conversion stage, and output stage). The input is global in-plane irradiation specific to the BIPV capacity, i.e., 1613 kWh/kWp, which is 100%; this energy was finally converted into 1193 kWh/kWp of useful electricity, which is around 74% of the input. The remaining 26%, i.e., -419 kWh/kWp of energy was lost in the BIPV system in the form of terrain shading, angular reflectivity, DC conversion losses, other DC losses, DC to AC conversion losses, transformer, and AC cabling losses, and availability losses are contributing to -0.27%, -3.56%, -14.38%, -2.50%, -2.50%, -1.50%, and -1% respectively.

The performance summary of the 1 MWp system was presented in Table 3. The energy lost due to terrain shading was observed to be -4 kWh/kWp; this is due to the variation in incident global-plane irradiance on the BIPV module due to the shading condition caused by nearby trees, buildings, or any obstacles. Loss due to angular reflectivity was also associated with the global in-plane irradiation; this contributes to -57 kWh/kWp. Angular reflectivity of the incident radiant energy from the sun onto the BIPV module surface causes the rise in the modules' temperature, which intern was reducing the conversion efficiency. A significant amount of loss, i.e., 223 kWh/kWp, was lost during the conversion of light energy into DC electricity at the BIPV module circuit. This is due to the BIPV crystalline technology's efficiency constraints (for the same 1 MWp BIPV system, under similar weather conditions, the energy loss during light to DC electricity conversion stage would vary concerning BIPV module technology).

Other DC losses such as power tolerance of DC modules, inter-row shading of modules, mismatch, and DC cabling losses were accounted collectively as -31 kWh/kWp. The energy losses due to the DC to AC conversion with the help of power converters or inverters are estimated to be around -31 kWh/kWp. Transformer and AC cables lead to -18 kWh/kWp of energy loss in the 1 MWp BIPV system. Energy loss due to the availability of a BIPV system is estimated as -12 kWh/kWp. The total energy loss in the 1 MWp BIPV system accounts for -419 kWh/kWp.

5. Suggestions for energy loss minimization

From this extensive study, few suggestions were made for improving the BIPV system performance, thereby reducing the energy losses. These suggestions would help in reducing the possible energy losses during the energy conversion stages.

- Avoiding all kinds of shading conditions by ensuring that the site area is free from shadows like buildings, trees, etc.
- The use of bi-facial photovoltaic modules for the installation could reduce the irradiance losses due to reflection.

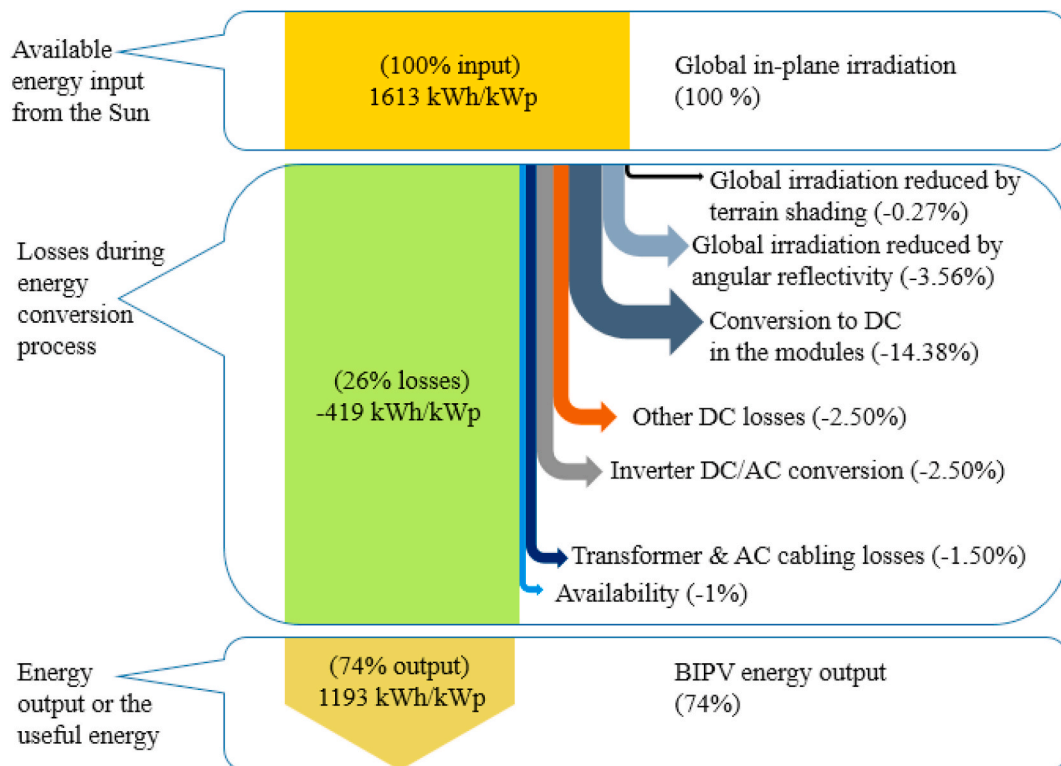


Fig. 7. Energy loss diagram of BIPV system.

Table 3
Summary of losses in the BIPV system.

Energy conversion stage	PV output (kWh/kWp)	Energy losses (kWh/kWp)	Cumulative Performance ratio (%)
Global in-plane irradiation (input)	1613	–	100.0
Global irradiation reduced by terrain shading	1608	–4	99.7
Global irradiation reduced by the angular reflectivity	1551	–57	96.2
Conversion to DC in the modules	128	–223	82.4
Other DC losses	1255	–31	75.9
Inverters (DC/AC conversion)	1224	–31	75.9
Transformer and AC cabling losses	1205	–18	74.7
Availability	1193	–12	74.0
Total system performance	1193	–419	74.0

- BIPV module cooling methods to be adopted would reduce the module temperatures, thereby increasing the energy conversion efficiency.
- Use energy-efficient and fast, responsive electrical components such as power converters and other grid feed-in facility equipment.
- Use appropriate DC cable sizes as per the possible ampere rating in each stage of the BIPV system.
- BIPV array configuration should be made effective as per the input DC conditions of the power converter, and the shade of one array string over the array should be eliminated.
- Reconnection of BIPV arrays would be a recommended option for minimizing the mismatch losses. This would help in reducing the losses due to shadow patterns on the BIPV array.
- Incorporating the maximum power point tracking converters in the electrical system of BIPV will be helpful.
- Maintenance of the transformer should be done regularly, like testing the transformer oil levels, loading levels, etc.
- Appropriate AC cable sizes and selection are to be done based on the current rating of the systems and the connected load.
- Be cautious about the maintenance and other issues related to the BIPV system. Hence one should have regular inspections leading to the monitored and test reports.
- Cleaning of BIPV arrays for overcoming soiling losses was one significant aspect, especially needed when BIPV systems were installed in dust and sand-prone sites. Soiling BIPV could even be a severe issue that affects the system performance when humid conditions are dominant.

Important points and parameters to be considered under loss investigation of the BIPV system are shown in Table 4. They are briefly discussed along with the reasons for the loss, possible loss (either irradiance loss or heat loss, or energy loss). Suggestions were also proposed considering each parameter responsible for energy loss in the BIPV system [42–47].

6. Conclusions

In this study, various losses that affect the electric potentials in the BIPV system proposed for the pitched roof were investigated. After analyzing the performance data, the losses in each stage of energy conversion were quantified and discussed. From this extensive study on energy losses in the BIPV system, the following conclusions were drawn:

- The proposed BIPV for roof buildings at UMP, Pekan campus showed the best performance regarding electrical potentials under Malaysia's tropical weather conditions, thereby promoting campus sustainability.
- The proposed roof-mounted BIPV system of the UMP Pekan in Singapore showed a decent averaged performance ratio of 74% and showed a fluctuation between 73.6 and 74.8%. Over the year, starting from January to December. This fluctuation seems to be very small and due to the tropical weather conditions.
- Over a year, the highest monthly and daily sum of specific electricity productions were recorded as 118.4 kWh/kWp, and 3.95 kWh/kWp respectively in April and the lowest as 68.3 kWh/kWp, and 2.20 kWh/kWp respectively in December.
- The percentual share of electricity production was observed to fluctuate in the range of 5.7–9.9% over a year. The main reason for this is the variation observed in the incident irradiance potentials on the BIPV array.
- The partial performance ratios in each stage of the BIPV energy conversion system were recorded as 99.7% for global irradiance by terrain shading, 96.4% for global irradiance by angular reflectivity, 85.6% for DC energy conversion, 94.5% for other DC loss stage, 97.5% for power converter or inverter stage, 98.5% for energy transmission stage through the transformer and AC cabling, and 99% for grid availability stage.
- Irradiance loss due to terrain shading and angular reflectivity was estimated as –4 kWh/kWp and –57 kWh/kWp, which contributes 0.27%, and –3.56%, respectively. These losses are due to the shade conditions on the BIPV array and could even result in hotspot issues. If the BIPV array could be installed without these losses, the BIPV system's PR could increase by 3–3.8%.
- A significant amount of loss is observed during the irradiance to DC energy conversion, i.e., 223 kWh/kWp contributes –14.38% of the total energy, other DC losses around –31 kWh/kWp contributes –2.50%, and DC to AC conversion losses around -1 kWh/kWp contributing to –2.50%.
- During the transmission of AC energy from the inverter output to utility, transformer, and AC cables, losses arise, and loss is estimated as –18 kWh/kWp contributing to –1.50% of total energy.

Table 4

Important points and suggestion to limit the losses in the BIPV system.

Energy conversion stage	Parameters to be concentrated	Reasons	Possible loss	Suggestions for minimizing the loss
Global irradiation reduced by terrain shading	-Irradiance, -Solar elevation, -Solar azimuth, -horizon -Shading	-Terrain shading -Scattered -Site elevation, -Slope inclination -Azimuth angle	Irradiance loss	-Avoid shading conditions of terrain by considering the appropriate positioning of the BIPV system
Global irradiation reduced by the angular reflectivity	-Solar elevation, -Solar azimuth, -clearness, -BIPV module texture and properties	-Angular reflectivity -BIPV module texture -Ground or installation base texture	Irradiance loss	-One of the possible ways is to use Bi-facial photovoltaics (this can be further researched)
Conversion to DC in the modules	-Air temperature, -BIPV module type, -Mounting configuration, -Relative humidity -Wind speed -Module temperature	-High module temperature leads to energy loss -The mounting configuration will influence temperature variation	DC energy loss	-Use the BIPV module cooling method to reduce the temperature -Install with a little air gap to allow the airflow -Have an explicit knowledge about the temperature coefficients of the module.
Other DC losses	-External shading, -Inter-row shading -Pollution -Soiling -Bird dropping -Snow -Frost -Cables -Mismatch	-Shadow generated by external hindrances located close to BIPV array. Example: typical shading objects are inline roof or walls while a BIPV roof or façade system is considered, and others include side buildings, big trees, poles, wall fencing, etc. -Inter-row shading is caused in the BIPV installation; here, the BIPV installed in the front row will cast a shadow on the BIPV's installed in back rows. -Caused by sand, dirt, particulate matter, dust content, soiling, falling dry and wet leaves, and bird droppings. -Snowfall and frost -Ohmic losses -BIPV power plant topology is the reason for DC cable loss -Inadequate power properties between the BIPV modules and cables	Energy loss Energy loss through heat dissipation	-Avoid shadows by considering the site parameters. -Seasons influence of low sun elevation angle could be considered. -Cleaning the BIPV system regularly helps in minimizing the losses. -Adopt the best BIPV DC circuit topology. -Adapt to the decentralized string inverter concept. -Make sure that BIPV module has equal power properties when they are connected in series
Inverters (DC/AC conversion)	-The electrical load on the inverter, -Inverter DC input voltage, -Inverter efficiency -System voltage -DC-AC conversion ratio -PV capacity to inverter capacity ratio	-Voltage miss match -Capacity ratio designs between the BIPV array and inverter -Heating of the inverter due to overload	Energy loss	Inverter power curve with 15 min of DC pairs of the data. -Use of high-performance inverters. A better understanding of the weighted average efficiency from dissimilar power echelons was identified during the BIPV power system operation.
Transformer and AC cabling losses	Transformer: -Transformer operating conditions, AC Cables: -Cable connectivity, -Long-distance connectivity -High voltage	-Low voltage to high voltage conversion -Transformer oil conditions -Cable size depending upon the voltage levels -Cable length as per the distance between the inverter system to the transformer	AC energy loss	-AC system architecture should well design. -Ensuring less distance between the transformer and inverter system -Regular maintenance of the transformer -Cable inspections for its connectivity, resistance loss, etc.
Availability	-Age of the BIPV power plant, -Issues with inverter failure,	-Various factors like a failure of the components, -Alteration in power purchase agreements in excess power generation cases,	-Energy loss -Energy left without consumption	- Critical inspections and monitoring are needed to identify the well-being of the BIPV power plant components. -Ensuring the regular maintenance of the

(continued on next page)

Table 4 (continued)

Energy conversion stage	Parameters to be concentrated	Reasons	Possible loss	Suggestions for minimizing the loss
	-BIPV strings continuity, -Cable continuity, -Electrical connections, -Power purchase regulation with grid	-A lifetime of the BIPV system., hence the probability of failure increases with the system's age.		system components based on the lifetime. -A clear understanding of the power purchases regulatory norms in the excess power generation conditions. In the case of excess power generation where the grid fails to purchase, the BIPV power plant owner must look for alternate options for selling the power or storing the energy. -Grid regulations on the outage etc

- The average total losses in the BIPV system is estimated to be around 26% in the proposed BIPV system for tropical weather condition. This is equivalent to -419 kWh/kWp of specific energy.
- As a result of the loss analysis in BIPV systems, various reasons for the identified losses and suggestions were made for limiting these losses in the practical implementation.

The presented study on energy loss investigation showed how the losses were affecting the BIPV system electricity potential. In what way each loss is varying concerning the energy conversion stage was also elaborated. The results showed here were concerning the crystalline technology, and there are chances for these to vary with other BIPV technologies. Few suggestions were made to reduce these losses. Investigation results on energy losses would help enhance future studies on the BIPV system, considering this as reference work. However, under these tropical weather conditions, the proposed BIPV systems are viable and have a reliable operation contributing to the sustainable and energy-efficient infrastructure.

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CRedit roles

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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